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The design beam lifetime of 100h for LHC imposes stringent requirements on the residual gas density in the vacuum chamber. This density can strongly increase due to ion induced gas desorption, as it was observed for the first time in the ISR. In the LHC, the ion induced gas desorption may lead to pressure runaway and, consequently, to the loss of the proton beam. The beam current that can be stored is limited, being the residual gas ionisation rate proportional to the beam current. Given the geometry and the pumping speed of the chamber, there is a critical current, above which the gas density diverges. In this paper, the gas density profile and the stability conditions are evaluated for different sections of the LHC, both for the elements at cryogenic and room temperature. For the cryogenic elements, it is found that the stability at ultimate beam current (0.85A) can be guaranteed if a beam screen is interposed between the proton beam and the cold bore vacuum chambers. In the warm sections, baking and discharge cleaning can ensure stability if the appropriate pumping is provided.

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ION DESORPTION VACUUM STABILITY IN THE LHC THE MULTIGAS MODEL

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Abstract

The design beam lifetime of 100h for LHC imposes stringent requirements on the residual gas density in the vacuum chamber. This density can strongly increase due to ion induced gas desorption, as it was observed for the first time in the ISR. In the LHC, the ion induced gas desorption may lead to pressure runaway and, consequently, to the loss of the proton beam. The beam current that can be stored is limited, being the residual gas ionisation rate proportional to the beam current. Given the geometry and the pumping speed of the chamber, there is a critical current, above which the gas density diverges. In this paper, the gas density profile and the stability conditions are evaluated for different sections of the LHC, both for the elements at cryogenic and room temperature. For the cryogenic elements, it is found that the stability at ultimate beam current (0.85A) can be guaranteed if a beam screen is interposed between the proton beam and the cold bore vacuum chambers. In the warm sections, baking and discharge cleaning can ensure stability if the appropriate pumping is provided.

1 THEORETICAL

The vacuum stability was usually studied assuming that only one single gas species is present in the system [1,2]. In reality, several species coexist, as observed experimentally from the dominating peaks in the mass spectra measurements. The ions of the generic gas species can desorb other gas species. Therefore, the equilibrium equations for the gas density of each species will be cross-correlated [3,4].

Consider a system with two dominant gas species, namely A and B. In axisymmetric geometry, the equations for the volumetric molecular density $n(z,t)$; and the surface molecular density $s(z,t)$ of the species A, are given by:

$$V\frac{dn_A}{dt}=\left(\chi_{A,A^+}+\chi'_{A,A^+}\right)\frac{I\sigma_A}{e}n_A+ \\ +\left(\chi_{A,B^+}+\chi'_{A,B^+}\right)\frac{I\sigma_B}{e}n_B+\left(\eta_A+\eta'_A\right)\dot{\Gamma}- \\ -\alpha_A S_A\left(n_A-n_{eA}\right)-C_A n_A+u_A\frac{d^2 n_A}{dz^2}; \qquad (1)$$

$$A\frac{ds_A}{dt}=\alpha_A S_A\left(n_A-n_{eA}\right)-\eta'_A\dot{\Gamma}- \\ -\chi'_{A,A^+}\frac{I\sigma_A}{e}n_A-\chi'_{A,B^+}\frac{I\sigma_B}{e}n_B; \qquad (2)$$

where the indexes A and B refer to the species A and B respectively. The equations for the gas species B are obtained from the equations (1) and (2) by inverting the two indexes A and B.

The first two terms on the right hand side of equation (1) account for the ion induced desorption from the wall substrate and from the gas condensed onto the surface, the third term accounts for the photo-stimulated desorption from the wall and the condensed gas, the fourth term indicates that the volumetric density is limited by the thermal equilibrium density n_e, the fifth term accounts for the distributed pumping along the wall and the last term accounts for the axial molecular diffusion. It was assumed that the parameters are constant in time and do not depend on the axial co-ordinate z. The symbols of the equations correspond to: V and A are the vacuum chamber volume and the wall surface area per unit axial length; I is the proton beam current; e is the electron charge; σ is ionisation cross section of the residual gas molecules for beam protons; $\dot{\Gamma}$ is the photon intensity per unit axial length; χ is the ion stimulated desorption yield; χ' is the ion stimulated desorption yield of cryosorbed molecules; η is the primary photo-desorption yield; η' is the photodesorption yield of cryosorbed molecules; α is the sticking probability; $S=A\bar{v}/4$ is the ideal wall pumping speed per unit axial length, $\bar{v}$ being the mean molecular speed; $C=\rho\, k_t\, S$ is the distributed pumping speed of the beam screen holes per unit axial length, ρ the Clausing factor, k_t the beam screen transparency (i.e. the ratio of the pumping holes area to the whole beam screen area); n_e is the thermal equilibrium gas density; $u=A_c\,D$ is the specific vacuum chamber conductance per unit axial length, A_c is the vacuum chamber cross section; D is the Knudsen diffusion coefficient.

In quasi-static conditions, where $V\,dn/dt\approx 0$ and $A\,ds/dt\neq 0$, the gas densities of two gases system, $n_A(z)$ and $n_B(z)$, are described by a system of two differential equation of the second order in form:

$$\begin{cases} u_1 \dfrac{d^2 n_A}{dz^2} - c_1 n_A + q_1 + d_1 n_B = 0; \\ u_2 \dfrac{d^2 n_B}{dz^2} - c_2 n_B + q_2 + d_2 n_A = 0; \end{cases} \tag{3}$$

and the solution is in the form

$$\begin{cases} n_A(z) = \dfrac{q_2 d_1 + c_2 q_1}{c_1 c_2 - d_1 d_2} + C_1 e^{\sqrt{\omega_1}\cdot z} + C_2 e^{-\sqrt{\omega_1}\cdot z} + \\ \qquad + C_3 e^{\sqrt{\omega_2}\cdot z} + C_4 e^{-\sqrt{\omega_2}\cdot z}; \\ n_B(z) = \dfrac{q_1 d_2 + c_1 q_2}{b_1 b_2 - d_1 d_2} + K_1 e^{\sqrt{\omega_1}\cdot z} + K_2 e^{-\sqrt{\omega_1}\cdot z} + \\ \qquad + K_3 e^{\sqrt{\omega_2}\cdot z} + K_4 e^{-\sqrt{\omega_2}\cdot z}; \end{cases} \tag{4}$$

where

$$\omega_{1,2} = \frac{1}{2}\left(\frac{c_1}{u_1} + \frac{c_2}{u_2} \pm \sqrt{\left(\frac{c_1}{u_1} - \frac{c_2}{u_2}\right)^2 + 4\frac{d_1 d_2}{u_1 u_2}} \right)$$

with $c_1 = \alpha_A S_A + C_A - \left(\chi_{A,A^+} + \chi'_{A,A^+}\right)\dfrac{I\sigma_A}{e}$;

$$c_2 = \alpha_B S_B + C_B - \left(\chi_{B,B^+} + \chi'_{B,B^+}\right)\frac{I\sigma_B}{e};$$

$$q_1 = \left(\eta_A + \eta'_A\right)\dot{\Gamma} + \alpha_A S_A n_{eA};$$

$$q_2 = \left(\eta_B + \eta'_B\right)\dot{\Gamma} + \alpha_B S_B n_{eB};$$

$$d_1 = \left(\chi_{A,B^+} + \chi'_{A,B^+}\right)\frac{I\sigma_B}{e};$$

$$d_2 = \left(\chi_{B,A^+} + \chi'_{B,A^+}\right)\frac{I\sigma_A}{e}.$$

The constants C_i and K_i (i=1…4) are dependent on the conditions at the ends of vacuum chamber.

There are three most representative cases for the LHC:

1. The infinitely long vacuum chamber with sorbing walls, i.e. when the end conditions can be neglected.
2. A vacuum chamber, with or without a beam screen, between two pumps.
3. A vacuum chamber without a beam screen between two vacuum chambers with a beam screen.

For all these cases, the gas density n increases with the beam current I and tends to infinity at the *critical current* I_c. The vacuum will be stable as long as the beam current is lower than the critical current.

2. INPUT DATA FOR SIMULATIONS

The main parameters for vacuum stability estimations are the ion stimulated desorption yields. These values were measured at CERN [5–8] but they are not directly applicable for the LHC case and are extrapolated from the existing experimental data (see Table 1). The ion stimulated desorption yield depends on the ion mass and energy, the surface conditions and the condensed gas surface density.

As it was shown in [9], there are two dominant gas species in the cryogenic sections of the LHC: H_2 and CO. At room temperature, instead, the vacuum stability depends mainly on CO and CO_2, and on CH_4 if the vacuum chamber is pumped by getters.

The average ion impact energy in the LHC arcs and the long straight sections was estimated in [10] to be 500 eV for H_2^+ and 300 eV for CO^+ and CO_2^+.

Table 1. Ion stimulated desorption yields

Gas	Impact energy	H_2	CH_4	CO	CO_2
χ (molecules/ion)					
H_2^+	500 eV	0.8	0.045	0.28	0.09
CH_4^+	300 eV	2.6	0.17	1.4	0.45
CO^+	300 eV	4.3	0.3	2.8	0.9
CO_2^+	300 eV	5.2	0.39	3.9	1.26
χ'_{max} (molecules/ion) at more than 3 monolayers					
H_2^+	500 eV	8000	–	20	20
Ar^+	500 eV	15000	–	25	25

3. THE CRYOGENIC ELEMENTS OF THE LHC

In the present work the vacuum stability was analysed for all the elements of the LHC except the interaction regions. The critical current for the single LHC cryogenic elements and for the whole unit (Q1–Q3, D2+Q4, D1+DFB) of the LHC as in the baseline design (LHC Optic Version 6.0) is evaluated and presented in Table 2. The vacuum is considered unstable (labeled "no") if the ratio between the calculated critical current and the LHC design ultimate current is less than 2, stable (labeled "yes") otherwise. A safety factor of 2 is introduced because the used parameters are affected by considerable uncertainties and because the pressure inside the vacuum chamber increases very rapidly as the current approaches its critical value.

4. THE ROOM TEMPERATURE ELEMENTS OF THE LHC

In a room temperature vacuum chamber all gases are present. Nevertheless, for the ion stability only CO and CO_2 play a significant role, due to lower effective pumping speed and the higher ion stimulated desoption yield than for other gas species. If the operating current is much lower than the critical value, the dominant gas will be H_2. When the operating current is close to the critical value, the dominant gas is *CO*.

In the case of LHC, most of the unbaked room temperature sections result to be unstable. To achieve stability, *ex-situ* glow discharge cleaning and *in-situ* bake-out is the most effective remedy, since this would reduce the ion stimulated yield by a factor of about 6, and, therefore, would increase the critical currents by the same factor. On the other hand, it is found that if the pumping speed at the chamber ends is augmented by a factor of 4, the critical current will increase only by about 50%. In conclusion, vacuum conditioning is strongly recommended.

Table 2. The ion stability of different elements of the LHC (v6.0).

Elements	I_{max}, (A)	I_c, (A)	Domin. gas	$\frac{I_c}{I_{max}}$	Stable or not
Arcs					
Beam screen	0.85	13.8	CO	16	Yes
Inter-connec-tions		4.6	CO	5.4	Yes
		1.54	CO	1.8	No
IR1, IR5, IR2 and IR8					
Q1–Q3	1.7	0.86	H_2+CO	—	No
D2+Q4	0.85	0.74	H_2+CO	—	No
Q5, Q6		1.5	H_2+CO	1.7	No
Q6,Q7 with b.s.		13.8	CO	16	Yes
IR4					
Q3, Q4	0.85	1.8	H_2+CO	2.1	Yes
Q5		1.5	H_2+CO	1.8	No
Q6+D3		0.68	H_2+CO	—	No
D4		1.1	H_2+CO	—	No
IR6					
Q4, Q5	0.85	2.8	H_2+CO	3.3	Yes
DFB		1.1	H_2+CO	1.3	No
For all elements with a beam screen or a liner					
With b.s.	1.7	13.8	CO	8.1	Yes
With liner		8.1	CO	4.8	Yes

5. CONCLUSIONS

1. In this paper the analysis of the vacuum stability against the ion induced desorption in the LHC is presented. It is shown that some elements of the long straight sections without a beam screen could be unstable.
2. A vacuum chamber with a beam screen is the best solution to guarantee the vacuum stability for any configuration of the LHC cryogenic vacuum system.
3. The chosen pumping units of 400 l/s for H_2 and about 200 l/s for *CO* are found to be adequate for the present design.
4. Many of the sections at room temperature could become unstable if they have a small diameter and thus small vacuum conductance. Adequate pumping must be achieved by closely spaced pumps. *Ex-situ* glow discharge cleaning and *in-situ* baking are required to reduce the ion stimulated desorption yield.

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